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FHWA/IN/JHRP-82/17

EFFECTS OF PORE SIZE DISTRIBUTION ON
PERMEABILITY AND FROST SUSCEPTIBILITY
OF SELECTED SUBGRADE MATERIALS

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JOINT HIGHWAY RESEARCH PROJECT

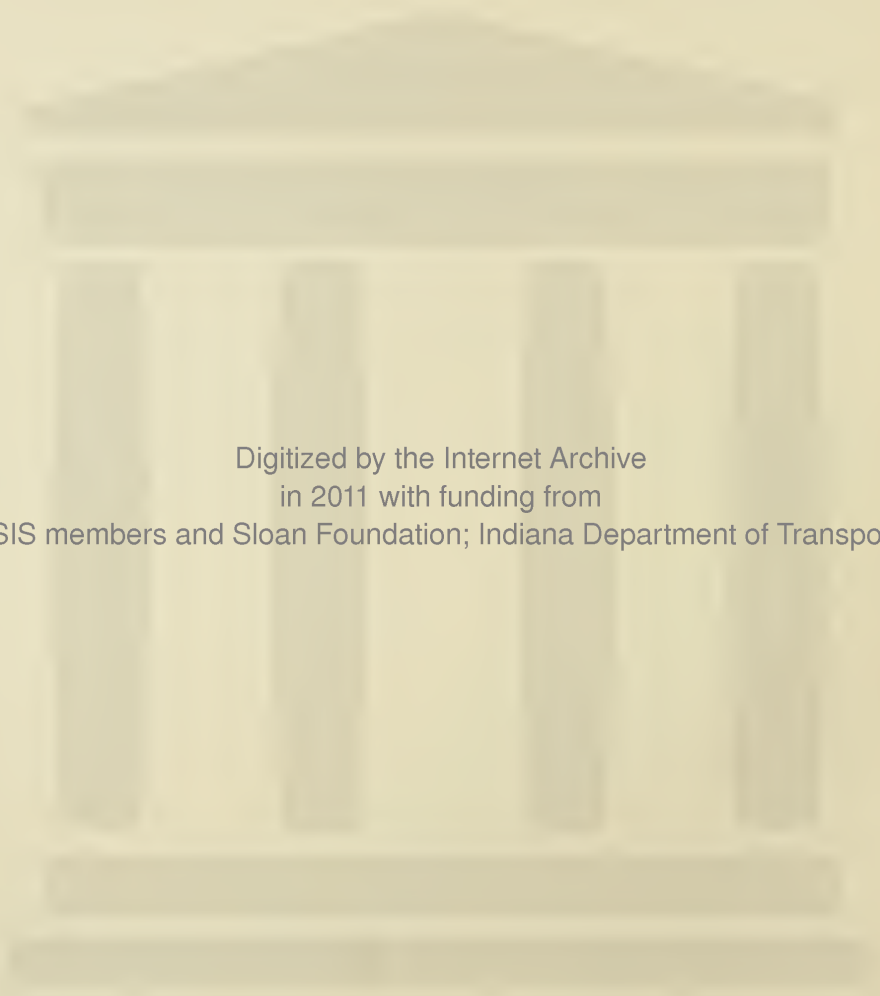
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FINAL REPORT

"Effects of Pore Size Distribution on Permeability and Frost
Susceptibility of Selected Subgrade Materials"

To: Harold L. Michael, Director
Joint Highway Research Project

From: L. E. Wood, Research Engineer
Joint Highway Research Project

October 26, 1982
Revised: May 17, 1983
Project: C-36-5N

File: 6-6-14

Attached is the Final Report on the HPR Part II Study entitled "Effects of Pore Size Distribution on Permeability and Frost Susceptibility of Selected Subgrade Materials". The report has been co-authored by Drs. L. E. Wood, A. G. Altschaeffl, and C. W. Lovell of our staff.

The results of this study clearly indicate that pore-size distribution serves as an excellent, sensitive characterization of soil fabric. This fabric, in turn, controls the engineering behavior of the soil. This report shows that the fabric can be controlled by appropriate selection of compaction variables for the soil. Indeed, it is shown that the most important variable controlling soil fabric is the water content at the time of compaction in relation to the optimum water content for that soil for the equipment and energy being used.

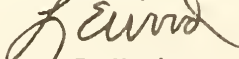
There are presented in this report several correlations that indicate properties can be predicted quantitatively from pore-size distributions. In addition, the prediction of the in-service equilibrium water content of a compacted soil is clearly delineated.

This study suggests we are on the threshold of being able to assure a given property magnitude in the field compacted soil in-service. The pore-size distribution is the vehicle that will allow determination of the compaction procedures that will create the suite of properties that the engineer desires for that project.

A plan is presented to introduce the findings of this study to the practitioner.

This Final Report is submitted for review and approval as fulfillment of the objectives of this project.

Sincerely,



L. E. Wood
Research Engineer

cc: A. G. Altschaeffl
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FINAL REPORT

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Susceptibility of Selected Subgrade Materials".

by

L. E. Wood
A. G. Altschaeffl
C. W. Lovell

Joint Highway Research Project
Project No: C-36-5N
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and the

U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data represented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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16. Abstract It is the thesis of this project that the fabric of a soil, i.e., the composition and arrangement of constituent particles, controls its engineering behavior. In addition, it is believed that the fabric can be described quantitatively by its pore size distribution. Magnitudes of properties can be predicted using pore-size distributions. Results of this study also clearly show that criteria for frost susceptibility based upon grain-size distributions are inadequate; pore-size based criteria are far superior for they acknowledge that a given soil can, and will, exist at many different pore sizes in its existence. A technique has been presented for the useful prediction of the in-service equilibrium water content of compacted clay. Pore size measurements in clean sand have been made for the first time by the use of trace amounts of thermally sensitive polymers which allow retention of the sand fabric. The results of this study suggest we are on the threshold of being able to assure a given property magnitude, in-service, of field compacted soil. The pore size distribution will allow the determination of the compaction procedures that will create the suite of properties that the engineer desires for the project. Thus it is felt that these results are of sufficient importance and promise to warrant an implementation program.			
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HIGHLIGHT SUMMARY

This is the Final Report for this project. It represents a summary of the tasks completed by various researchers as well as other associated work.

It is the thesis of this project that the fabric of a soil, i.e., the composition and arrangement of constituent particles, controls its engineering behavior. In addition, it is believed that the fabric can be described quantitatively by its pore size distribution, as obtained by mercury porosimetry. The components of this project, as summarized herein, prove the validity of this thesis.

Pore-size distribution can now be obtained routinely. They serve as excellent, sensitive characterizations of soil fabric. The fabric controls the engineering properties, and magnitudes of properties can be predicted using pore-size distributions. The fabric is created by the details of placement of the soil. The pore-size distribution is quantitatively related to the variables of compaction. The most important variable determining the soil fabric is the water content at the time of compaction in relation to the optimum water content for that soil for the equipment and energy being used.

Results of this study also clearly show that criteria for frost susceptibility based upon grain-size distributions are inadequate; pore-size based criteria are far superior for they acknowledge that a given soil can, and will, exist at many different pore sizes in its existence.

A technique has been presented for the useful prediction of the in-service equilibrium water content of compacted clay. In addition, prediction relations are presented for such properties of A-6, A-7-6 soil as water permeability, compressibility characteristics, strength characteristics, and swelling tendencies.

Pore size measurements in clean sand have been made for the first time by the use of trace amounts of thermally sensitive polymers which allow retention of the sand fabric.

The results of this study suggest we are on the threshold of being able to assure a given property magnitude, in-service, of field compacted soil. The pore size distribution will allow the determination of the compaction procedures that will create the suite of properties that the engineer desires for the project. Thus, it is felt that these results are of sufficient importance and promise to warrant an implementation program.

Conclusions

1. Pore-size distributions of soils can readily be obtained, relatively quickly, in a replicatable manner. Such measurements now can be obtained routinely.
2. Pore-size distributions of soils serve as an excellent, sensitive, characterization of the fabric of soils.
3. The most important variable in determining the fabric of compacted soil is the water content at the time of compaction in relation to the optimum water content for that soil for the equipment and energy being used.
4. The fabric of soil, as described quantitatively by pore-size distribution, controls the engineering properties of the soil; properties magnitudes can be predicted quantitatively from pore-size distributions.
5. Grain-size distribution based frost criteria are inadequate for frost prediction. Pore-size based criteria are far superior; this project reports the first such prediction of heaving rate from pore-size distribution accounting for the fact that a given soil can exist at many different pore sizes.
6. Prediction techniques are presented for use for strength characteristics, compressibility characteristics, and swelling tendencies for an A-6, A-7-6 soil and soil mixtures.
7. A correction technique has been created to account for soil mineralogy effects upon water permeability predictions based upon pore-size distribution.
8. A technique has been presented for useful prediction of the equilibrium water content of a subgrade soil in-service.

9. Total porosity and grain size distribution are inadequate criteria for prediction of water permeability. Pore size criteria are much better, and their use is reported here for the first time.
10. Prediction of water permeability from pore size measurements is an attractive alternative to direct permeability measurement, especially for clayey soils.

Introduction

This report represents a summary of the work done by the various researchers associated with this project. It attempts to show that the project, indeed, fulfilled its purposes. These endpoints have been presented as conclusions in this report.

In order for the reader to properly digest the contents of this report, the context of the project must be understood. In clayey soils we believe the fabric, i.e., the composition and arrangement of constituent particles, controls engineering behavior. In addition, the fabric is controlled by the details of how the soil is created or placed; the most important variable controlling the fabric of compacted clays is believed to be the water content at the time of compaction as it relates to the "optimum water content" for that soil for the equipment and energy being used. We believe these basic premises are substantiated in this report; the reader is urged to recognize this as the context within which this report is written.

The project history is first presented because in this we find the foregoing context beginning to be firmly developed. There follows a very brief summary of each of the tasks itemized in the project.

The assembly of data to clearly show the interdependence of soil properties and fabric and of fabric descriptors and compaction variables is presented next. These correlations were performed outside the context of formal tasks; in essence, they are a result of the tasks because the tasks showed the viability of the concepts. These results clearly show that pore size distribution serves as a sensitive measure of fabric, and that fabric is sensitive to how the soil was placed in compaction.

An item capable of implementation is presented next. The prediction of in-service equilibrium water content is now believed capable of routine performance. The details of the procedure are presented in this separate section.

The last items in this report are Conclusions and a Plan for Implementation. References include project Interim Reports because this final report is not intended to be self-standing.

Background and Project Chronology

This project was motivated by the continuing difficulties encountered by the engineer in unravelling the problems caused by soil-water interaction and the changes in behavior produced therefrom. The importance of soil fabric could be verified in such a context; this wish to prove the thesis that fabric controls behavior was the beginning. It is this thought that is carried through the sections of this report.

The wish to describe quantitatively the fabric of soil has existed for some time. Mitchell (1956) was among the first to make serious efforts. Several others, e.g., Martin (1964), Morgenstern and Tchalenko (1967), and McGown, et al (1980), have also made contributions to this question. At Purdue University, research has been conducted for a number of years on characterizing soil fabric by using the distribution of the sizes of the void spaces (pores) in the soil (Ahmed (1971), Diamond (1971), Sridharan, et al (1971), Bhasin (1975)). This pore-size distribution (PSD), as obtained from mercury porosimetry, has been found to be a sensitive characteristic with much potential for use.

The success with characterization of soil fabric by its pore-size distribution suggested much promise in using these data to understand any phenomenon in which water moves through soil voids. At the same time, then, the matter of water retention in the soil voids would also be treated.

With the above in mind, a proposal for research was submitted for HPR funding. The Phase I of this proposal was intended to clearly show that pore size distributions do serve as a possible fundamental parameter for use in predictions of behavior involving water flow. It addressed frost action behavior and frost-susceptibility criteria, and it included work with freezing rates, permeability, and the effects of clay mineralogy upon the water flow relations. Phase I was approved effective April 1, 1976.

An Interim Report was approved December 21, 1977 for Task A as entitled "Frost Heaving Rate of Silty Soils as a Function of Pore Size Distribution" by M. A. Reed (Report No. JHRP-77-15, September 1977).

An Interim Report was approved September 11, 1978 for Task B as entitled, "The Relation Between Permeability and Pore Size Distribution of Compacted Clayey Silts", by I. Garcia-Bengochea (Report No. JHRP 78-4, May 1978).

The results of Tasks A and B of Phase I were believed to clearly show that pore-size distributions are fundamental for use in predicting soil-water flow behavior. Thus, a proposal was submitted on April 4, 1978 for an extension and expansion of the study. This proposal extended the time for Task C (because of an inability to identify a qualified researcher) and added two additional Tasks (D and E). This proposal was approved effective July 19, 1978 (under letter from Mr. C. A. Culp, FHWA).

An Interim Report was approved April 8, 1981 for Task D as entitled, "The Fabric of a Medium Plastic Clay Compacted in the Laboratory and in the Field", by D. M. White, (Report No. FHWA/IN/JHRP-80-10, August 1980).

An Interim Report was approved October 6, 1981 for Task E as entitled "Pore Size Distribution of Sandy Soils and the Prediction of Permeability" by C. H. Juang (Report No. FHWA/IN/JHRP-81-15, August 1981).

An Interim Report was approved September 15, 1982 for Task C as entitled "Prediction of Soil Equilibrium Water Content and Mineralogy Effect on Permeability Using Pore Size Distribution", by S. Prapaharan, (Report No. FHWA/IN/JHRP-82/12, July 1982).

Task Summaries

Task A - Correlation of Pore-Size Parameters with Frost Susceptibility

Background ; Reed (1977).

Popular frost susceptibility ratings are based upon, (a) soil texture or gradation, and (b) frost heaving rate . The former are approximate, since a given soil can be compacted with a range of densities and fabrics, and would accordingly demonstrate a variety of frost susceptibilities. Pore size distribution has promise as a frost susceptibility index because it contains both the total porosity (density measure) and the relative amounts of pore sizes (fabric measure). This research produced experimental evidence of the value of pore size distribution for a susceptibility index.

Experimentation

Soils were clayey silts, composed of mixtures of kaolin and Indiana loess. These soils were compacted by kneading to a variety of efforts and moisture contents. Frost susceptibility was directly rated by a rapid freeze test. Replicate small samples were used for pore size distribution. Constant volume drying of the pore size samples was by freeze drying; pore size measurement was by mercury intrusion. All experimental techniques are described in detail in Reed (1977), and such testing can be repeated by following these procedures.

The independent variables in the research were: (a) soil type, (b) compactive effort, and (c) compaction water content. The dependent ones were: (a) compacted density (or porosity), (b) size distribution of porosity, and (c) rate of frost heaving. To demonstrate the utility of pore size distribution as a frost susceptibility index, it was statistically related to frost heaving rate.

Conclusions

Examination of the experimental pore size distribution curves showed that the pore space below about 0.4 micrometers was approximately constant. Pore space above about 3 micrometers was very much affected by the compaction water content and effort, and the frost heaving rate for a given soil varied greatly with the quantity of these larger voids. The regression techniques and equations developed are given in detail in Reed (1977), and could be repeated by following the procedures described herein.

The results of the study were positive and encouraging to further efforts to develop pore size distribution as a soil frost susceptibility index.

Task B - Relationship Between Water Permeability and Pore-Size Distribution;
Garcia-Bengochea (1978).

Background

Practical prediction equations for water permeability are based upon gradation and/or density (or porosity). These equations are not reliable for fine-grained soils, since they do not account for the structural arrangement of the soil solids (called fabric). Pore size distribution has the capacity to reflect changes in fabric, and to approximate the sizes of channels through which the water must move. This research demonstrated the value of pore size distribution in the prediction of saturated permeability.

Experimentation

Soils were mixtures of kaolin and Indiana loess. They were compacted by a kneading mode to various water contents at various values of compaction foot pressures. The soil remained in the lucite compaction mold for back-pressure saturation and for falling head permeability measurements. After the water permeability test on a sample was complete, smaller samples were taken from it for freeze drying and for pore size measurements by mercury intrusion. All experimental details are given in Garcia-Bengochea (1978), and all test setups can be recreated by following the instruction contained therein.

The independent variables were: (a) soil type, (b) kneading compactor foot pressure, and (c) compaction water content. Dependent variables were: (a) compacted density (or porosity), (b) size distribution of porosity, and (c) coefficient of permeability. Three permeability prediction models were developed containing some function of pore size distribution. These were:

(a) variable diameter capillary model; (b) Marshall (probabilistic) model; and (c) hydraulic radius model.

All prediction equations took the following form:

$$k = C_s \cdot \text{PSP}$$

where k is the Darcy permeability,

C_s is like a shape factor,

and PSP is the pore size parameter

(Garcia-Bengochea, 1978, page 24).

Conclusions

Pore size distributions were typically bimodal. The small mode occurred at about 0.1 micrometer and increased in frequency with the percentage of kaolin. The larger pore mode occurred between 1 and 10 micrometer, and varied with the compaction variables. Dry side compaction and low compactive effort each produced more large pores in the soil; wet side compaction resulted in fewer large pores. Permeability values were higher in the former case, lower in the latter. The range of permeability values measured was about 3×10^{-8} to 3×10^{-5} cm/sec.

Regression equations between permeability (k) and pore size parameter (PSP) took the form:

$$k = C_s \text{PSP}^b$$

where C_s and b are regression constants.

All three models, identified above, yielded equations with strong statistical credentials. The process of developing predictive equations for permeability from pore size distribution measurements on fine grained soils is clearly defined in Garcia-Bengochea (1978). It can be repeated by following the details given.

The results are highly encouraging, and indicate that pore size distributions have a valuable role in the development of prediction equations for permeability.

Task C - Examination of the Non-Permeable Porosity in a Soil (and In-Situ Equilibrium Water Content); Prapaharan (1982).

Background

Many soils contain pores sufficiently small so that soil mineralogy influences water flow. An adsorbed water layer is believed to be created, and this reduces the pore size available for flow.

This study investigates the effects of mineralogy upon permeability. It also examines whether pore-size distributions can be used to predict what will be the soil suction in-service equilibrium, because suction is related to pore-size; soil suction can thus be related to equilibrium water content in-service by utilizing moisture characteristic curves.

Experimentation

Both naturally occurring soils and artificial mixtures of silt and kaolin (as used by other researchers) were used in this study. The natural soils were compacted by impact compaction, whereas the mixtures were prepared by kneading compaction. The natural soil specimens were obtained through the cooperation of researchers at the University of Illinois.

Mercury intrusion was used to obtain the pore size distribution data on freeze-dried specimens. Air permeability was determined on dehydrated samples using "dried" air. By comparing the air permeability to the water permeability for specimens prepared in the same way by other researchers, the effect of soil mineralogy was obtained. Clay content and composition, indeed, had an effect. A correlation between the ratio of air to water permeability and the soil activity was accomplished. Thus, the effects of the mineralogy on permeability were established.

The soil-moisture characteristic curves (i.e., the relation between soil suction and water content) for the natural soils had also been supplied by the University of Illinois researchers. Pore-size distribution data were analyzed and it was shown that they accurately can be used to predict the practical soil moisture characteristic curve. This, then, allows prediction of equilibrium water content in much shorter time.

Conclusions

There is no single "effective diameter" which characterizes the pore-size distribution adequately for correlation purposes. A combination of pore-size distribution descriptors appears to be necessary.

Air permeability can be predicted from pore-size distribution parameters. The models do not, however, also predict water permeability with any accuracy. A correlation was accomplished between air and water permeability. Soil activity appears to be a vehicle for accounting for mineralogic effects in permeability prediction by using a correlation between activity and the air to water permeability ratio.

The use of pore-size distribution data to predict the soil moisture characteristic curve allows prediction of equilibrium water content in terms of minutes or hours instead of weeks in the more usual way. The predictions appear adequate for soils that will be as much as 25 meters (75 feet) above the Free Water Level.

The use of pore-size distributions as predictors of behavior is clearly evident when water flow is involved. The effects of soil clay mineralogy are, however, not simply defined. For example, effects upon permeability appear to differ from effects upon soil freezing rate. To accomplish predictions, then, requires each phenomenon to be addressed individually if the relationships are to be determined.

Task D - Pore-Size Distributions of Field and Laboratory Compacted Soil;
White (1980).

Background

This task serves as a bridge between this project and a companion HPR project which was conducted at Purdue University entitled "Improving Embankment Design and Performance". The reader is encouraged to secure the final report for that project which is forthcoming in FY 84. The companion project has the objectives of (1) improving the predictability of the field behavior of compacted soil, and (2) to create procedures which will allow development of suitable field compaction specifications that will assure a specific desired magnitude of behavior parameters. Several properties are addressed including various parameters associated with strength behavior, compressibility, volume change upon soaking, and the tendency to swell induced by compaction.

The companion report demonstrated that laboratory relationships between compaction variables and behavior parameters are different from those of the field-compacted soil. Differences in the soil fabric produced by the compaction are believed the cause and explanation of the discovered differences in relationships. Pore-size distributions are used as measures of soil fabric. Thus this task examines whether, indeed, it is possible to show that laboratory and field produced soil fabrics are, in fact, different.

Experimentation

The soil was a medium plastic silty clay (A-6, A-7-6) that had been compacted in a test embankment for the companion project by two different compactors in the field. Specimens were taken from samples that had been compacted at different water contents with different energies to different densities.

The same soil was also compacted in the laboratory with Proctor impact and Hveem kneading procedures. Compaction water contents and energies and densities were varied to cover the practical range.

Pore-size distributions were obtained on replicate specimens from both the laboratory and field compacted soil. Many possible descriptors of the pore-size distribution curves were defined and their magnitudes established. Of the many descriptors, those with large variance, non-normality, or lack of correlation with compaction variables were discarded. The remaining descriptors were used for regression analysis. The purpose was to see if the differences in descriptors for the differently created fabrics were statistically significant.

Note: The samples of the field compacted soil from which the tested specimens for this task were taken had all been obtained by drive-sampling techniques. In a companion HPR project push-samples had also been obtained in order to learn if drive-sampling produced more sample disturbance. This task did not test the push-sample specimens because of timing and personnel difficulties.

The companion project examined the unconfined compression strengths of specimens taken by both sampling methods. Statistical examination of the results indicated no significant difference could be discovered in the strengths obtained by the 2 sampling methods. We concluded that the drive sampling technique produced samples that are the equivalent of those taken by the push technique in this compacted clay.

Conclusions

Pore-size distribution curve descriptors involving the logarithm of the 50th and 70th percentile diameter and the percentage of pore volume that was intruded were the most useful for comparisons. The descriptors were affected primarily by the deviation of the compaction water content from the optimum for the respective compaction variables. Energy and energy-water content interaction terms were also significant.

The fabrics produced by the 2 laboratory compaction procedures were statistically the same. The fabrics of the laboratory compacted soil were statistically different from those of the field compacted soil; the differences were more pronounced on the dry side of optimum water content. Statistical differences in fabrics also were found to be produced by the 2 different field compactors on dry side compaction only.

These results suggested that we now are able to quantitatively compare fabrics of compacted clays. We now hope to quantitatively attribute differences in engineering behavior to fabric differences; in addition, then, the prospect exists that we will be able to control behavior by controlling fabric through proper selection of compaction variables.

Task E - Permeability of Sandy Soils as Affected by the Distribution of Porosity; Juang (1981).

Background

Sandy soils are frequently used in highway embankments, subgrades, and subbases because of their good strength, compressibility, and drainage. The quality of drainability varies considerably depending on the presence of fines, the gradation of the sand and the density at which the sand is placed.

Permeability may either be established by performing physical testing or through the use of prediction equations. Existing prediction equations are based exclusively upon grain size distribution, not the sizes of voids through which flow actually takes place.

Previous work has shown clearly that pore-size distribution was closely correlated with water permeability for silty clay soils. Pore-size distributions were also sensitive to how the soil was formed and under what water content and energy of compaction.

This task serves to extend the range of soils for which predictions of permeability are possible in much better manner than has been possible in the recent past.

Experimentation

A sand and two sand-clay mixtures were used. The mixtures were prepared by kneading compaction to various densities at various water contents produced by various compaction energies. Pluvial (falling through air) compaction was used to prepare compacted samples of sand. Falling head permeability tests were performed

on the prepared samples. Pore-size distributions were obtained by mercury-intrusion on specimens taken from each of the prepared samples. A special technique, i.e. the addition of a trace amount of phenolic resin during compaction and subsequent heating to cause development of cohesion, was created to allow testing specimens of sand which otherwise would have collapsed under their own weight. A new model was defined to predict permeability from pore size distribution data; it has a probabilistic basis as well as an apparent lesser degree of empiricism than previously used models.

$$k = \frac{\gamma_n^2}{32\mu} \int \int \tilde{x}^2 \cdot G(x_j) \cdot f(x_i) \cdot f(x_j) \cdot dx_i dx_j$$

where $G(x_j) = e^{-\left(\frac{x_i - x_j}{V}\right)^2}$

$$V = v \cdot x_j$$

$$\text{and } V = -6.15 - 40.07 \left(\frac{D_{40}}{D_{25}}\right) + 118.79 \left(\frac{D_{40}}{D_{10}}\right) - 78.35 \left(\frac{D_{60}}{D_{10}}\right)$$

Conclusions

The technique for preparation of specimens of cohesionless soils appears to have been successful. The new model for prediction also performed well and appears to be valid for both sandy soils and the soils of low plasticity used by previous researchers.

The large pore mode and its probability density appear to be excellent indicators of changes in fabric produced by changes in soil compaction variables. The pore size density function in the small pore region may serve as a signature of clay "type", but only the presence of kaolin was involved in this study.

Correlation of PSD with Other Soil Properties

The original motivation for the project involved the idea that fabric controls clayey soil behavior, and that PSD is a measure of the fabric.

In this project, frost heaving rate, and permeability were correlated with PSD characteristics. It is reported that PSD varies with variations in compaction variables, but the quantitative relations were not developed. In the companion project, previously described, the properties of the compacted soil were correlated with the compaction variables, and the correlations are quantitative in the form of "prediction equations for the properties".

Task D of the subject project serves as a bridge between the 2 projects. This task created PSD descriptors which related PSD to compaction variables for the soil for which (many) properties data existed. Correlations were attempted for the A-6; A-7-6 soil of moderate plasticity between PSD descriptors and properties. The results are presented in Table 1.

Correlation of Fabric Descriptors with Compaction Variables

The correlations are good between pore-size descriptors and the various property magnitudes for compacted soil behavior. Each property appears to have its own relationship with the various descriptors, and, thus, is controlled differently by the fabric.

It has been the thesis of this project that fabric is created and controlled by the variables of compaction. The pore-size descriptors are a measure of the nature of the fabric. Thus, to determine the relations between the descriptors and the compaction variables, correlations were performed by again using data from both projects. The results follow in Table 2.

Each of the descriptors is differently related to the compaction variables. The water content, as related to the optimum water content, is the controlling variable, for it has an overriding control on the descriptors. This, indeed, validates the thesis of the project.

LIST OF SYMBOLS FOR
TABLES 1 AND 2

A_f	= the Skempton A coefficient of failure
c'	= effective stress strength intercept (kPa)
D_{25}	= pore diameter where 25% of intruded volume is in larger pores
D_{50}	= pore diameter where 50% of intruded volume is in larger pores
D_{60}	= pore diameter where 60% of intruded volume is in larger pores
D_{75}	= pore diameter where 75% of intruded volume is in larger pores
D_{pk}	= pore diameter having largest porosity frequency
p_c	= compaction pressure (psi)
p_o	= simulated embankment pressure (psi)
p_s	= compactive prestress (psi)
PSR	= prestress ratio = $\frac{p_s}{p_c}$
Q_c	= as-compacted compressive strength (kPa)
R^2	= coefficient of determination - statistical measure of "goodness of fit"
SP	= swell pressure (psi)
$\frac{\Delta V}{V_o}$	= volumetric strain (%)
Δw	= water content relative to optimum moisture content (%)
γ_d	= dry density (pcf)
ϕ'	= effective stress strength angle (degree)
σ_c	= isotropic consolidation pressure (psi)

TABLE 1 Results of Regression for Field Compacted Properties Parameters

Compactor Type	Conditions for Application	Regression Model	R ²
Caterpillar	all	$A_f = -0.168 \left(\frac{D_{25} - D_{60}}{D_{75}} \right)^{\frac{1}{2}} - 0.658 \left(\frac{s}{\sigma_c} \right)^{\frac{1}{2}} + 0.836 \sigma_c^{\frac{1}{2}} + 5.04$	0.702
	all	$1-D \frac{\Delta V}{V} = 12.81 + 168 D_{75} + 5.5 D_{60} - 13.4 D_{pk} - 147 D_{75}^{\frac{1}{2}} + 26 D_{60}^{\frac{1}{2}} + 13 D_{pk}^{\frac{1}{2}} + 0.0575 p_o^{\frac{1}{2}}$	0.744
	all	$\text{Triaxial } \frac{\Delta V}{V} = 25.1 - 8.14 \left(\frac{D_{25} - D_{60}}{D_{50}} \right)^{\frac{1}{2}} + 3.77 \left(\frac{D_{25} - D_{75}}{D_{pk}} \right)^{\frac{1}{2}} - 95.7 \left(\frac{D_{75}}{D_{pk} \sigma_c} \right)^{\frac{1}{2}} - 1.55 p_s^{\frac{1}{2}}$	0.729
	all	$c' = 26.4 + 299 D_{60}^2 - 373 D_{75}^2 - 285 D_{50}^2 + 171 D_{25}^2 + 93 D_{pk}^2$	0.776
	all	$\phi' = -8.4 - 379 D_{60}^2 + 525 D_{75}^2 + 361 D_{50}^2 - 22.5 D_{25}^2 - 124.6 D_{pk}^2$	0.81
	all	$Q_c = 2024 D_{50}^2 - 50.3 D_{25}^2 - 378 D_{pk}^2 - 6087 D_{60}^2 + 4159 D_{75} + 7.5 \sigma_c^{\frac{1}{2}} - 102$	0.467
	all	$SP = 20.5 - \frac{1.4}{D_{75}} + \frac{9.82}{D_{60}} + \frac{0.32}{D_{pk}} - \frac{28.3}{D_{25}}$	0.748

TABLE 1 (continued)

Compactor Type	Conditions for Application	Regression Model	R ²
Rascal	all	$A_f = 0.74 - 0.76 \left(\frac{D_{25}^{-D}}{D_{50}} \right) + 1.93 \left(\frac{D_{25}^{-D} D_{60}^{\frac{1}{2}}}{D_{50}} \right) + 94.6 \left(\frac{D_{75}}{D_{pk} \sigma_c} \right) - 16.8 \left(\frac{D_{75}}{D_{pk} \sigma_c} \right)^{\frac{1}{2}} - 0.1365 p_s^{\frac{1}{2}} - 0.002 \sigma_c^{\frac{1}{2}}$	0.503
	all	$1-D \frac{\Delta V}{V} = 1.12 - 8.4 \frac{D_{60}}{D_{75}} + 25.7 \frac{D_{75}}{D_{pk}} + 3.7 \frac{D_{75}}{D_{pk}} - 0.82 \frac{D_{60}^{\frac{1}{2}}}{D_{pk}} - 7.39 \frac{D_{75}^{\frac{1}{2}}}{D_{pk}} - 2.2 \frac{D_{pk}^{\frac{1}{2}}}{D_{pk}} + 0.0937 p_o^{\frac{1}{2}}$	0.698
	all	$\text{Triaxial } \frac{\Delta V}{V} = -10.8 \left(\frac{D_{25}^{-D}}{D_{50}} \right) + 55 \log \left(\frac{D_{25}^{-D} D_{60}}{D_{50}} \right) + 146 \frac{D_{75}^2}{D_{50}} - 1.8 \frac{D_{pk}^2}{D_{75}} - 181 \frac{D_{75}}{D_{60}} + 82 \frac{D_{60}}{D_{pk}} + 6.4 \left(\frac{\sigma_c}{p_s} \right)^{\frac{1}{2}} + 4.23$	0.550
	all	$c' = 3.63 - 115 \frac{D_{60}}{D_{75}} + 154.5 \frac{D_{75}}{D_{50}} + 17.4 \frac{D_{50}}{D_{25}} + 8.1 \frac{D_{25}^2}{D_{pk}} - 1.33 \frac{D_{pk}^2}{D_{25}}$	0.747
	all	$\phi' = 23 + 172.7 \frac{D_{60}}{D_{75}} - 228 \frac{D_{75}}{D_{50}} - 22.8 \frac{D_{50}}{D_{75}} - 8.4 \frac{D_{25}^2}{D_{pk}} - 10.5 \frac{D_{pk}^2}{D_{25}}$	0.870
	all	$Q_c = 25.2 \left(\frac{D_{25}^{-D}}{D_{75}} \right) - 155.5 \left(\frac{D_{25}^{-D} D_{60}^{\frac{1}{2}}}{D_{75}} \right) - 3073 \frac{D_{75}^2}{D_{75}} - 116.5 \frac{D_{pk}^2}{D_{75}} + 458.6 \frac{D_{60}}{D_{75}} + 12.0 \frac{D_{25}}{D_{75}} + 8.64 (\sigma_c)^{\frac{1}{2}} + 212.2$	0.487

TABLE 1 (continued)

Compactor Type	Conditions for Application	Regression Model	R ²
Rascal	all	$SP = -0.107 - \frac{2.89}{D_{75}} + \frac{5.56}{D_{60}} - \frac{4.53}{D_{pk}} + \frac{18.37}{D_{25}}$	0.522
Rascal and Caterpillar	wet of optimum	$PSR = 23.4 D_{25} - 7.9 D_{60} + 1.2 D_{pk}^2 + 19.7 D_{60}^2 - 108.2 D_{75}^2$ $- 1.9 D_{pk}^2 - 0.032$	0.77
	dry of optimum	$PSR = 0.795 - 24.9 D_{75} + 10.9 D_{60} - 0.8 D_{pk} + 78.7 D_{75}^2$ $- 15.4 D_{60}^2 - 0.72 D_{pk}^2$	0.856

TABLE 2 Results of Regression for Pore Size Descriptors

Compactor Type	Regression Model	R ²
Caterpillar		
D ₆₀	$D_{60} = 3.28 + 1.78 \Delta w - 0.0268 \gamma_D - 0.0169 \Delta w \gamma_D - 55.4 \frac{\Delta w}{p_c^{\frac{1}{2}}} + 5.36 \Delta w \left(\frac{\gamma_D}{p_c} \right)^{\frac{1}{2}}$	0.745
D _{pk}	$D_{pk} = 13.85 + 2.73 \Delta w - 0.117 \gamma_D - 0.0264 \Delta w \gamma_D - 117.7 \frac{\Delta w}{p_c^{\frac{1}{2}}} + 11.33 \Delta w \left(\frac{\gamma_D}{p_c} \right)^{\frac{1}{2}}$	0.795
D ₅₀	$D_{50} = 5.66 + 2.74 \Delta w - 0.0465 \gamma_D - 0.0262 \Delta w \gamma_D - 86.84 \frac{\Delta w}{p_c^{\frac{1}{2}}} + 8.4 \Delta w \left(\frac{\gamma_D}{p_c} \right)^{\frac{1}{2}}$	0.753
D ₂₅	$D_{25} = 7.80 + 8.68 \Delta w - 0.0599 \gamma_D - 0.0821 \Delta w \gamma_D - 240.43 \frac{\Delta w}{p_c^{\frac{1}{2}}} + 23.2 \Delta w \left(\frac{\gamma_D}{p_c} \right)^{\frac{1}{2}}$	0.43
D ₇₅	$D_{75} = 0.779 + 0.965 \Delta w - 0.00612 \gamma_D - 0.00911 \Delta w \gamma_D - 27.7 \frac{\Delta w}{p_c^{\frac{1}{2}}} + 2.68 \Delta w \left(\frac{\gamma_D}{p_c} \right)^{\frac{1}{2}}$	0.698

TABLE 2 (continued)

Compactor Type	Regression Model			R ²
Rascal				
D ₆₀	$= - 3.14 + 1.52 \Delta w + 0.0264 \gamma_D + \frac{60.55}{p_c} + 1.97 \Delta w \left(\frac{\gamma_D}{p_c} \right) - 226.5 \frac{\Delta w}{p_c} - 0.0132 \Delta w \gamma_D$			0.39
D _{pk}	$= - 4.03 + 1.55 \Delta w + 0.034 \gamma_D + \frac{99.6}{p_c} + 1.43 \Delta w \left(\frac{\gamma_D}{p_c} \right) - 175.0 \frac{\Delta w}{p_c} - 0.0128 \Delta w \gamma_D$			0.39
D ₅₀	$= - 3.64 + 1.85 \Delta w + 0.0308 \gamma_D + \frac{79.0}{p_c} + 2.495 \Delta w \left(\frac{\gamma_D}{p_c} \right) - 288 \frac{\Delta w}{p_c} - 0.0159 \Delta w \gamma_D$			0.395
D ₂₅	$= - 7.28 + 1.97 \Delta w + 0.062 \gamma_D + \frac{153.2}{p_c} + 1.586 \Delta w \left(\frac{\gamma_D}{p_c} \right) - 191 \frac{\Delta w}{p_c} - 0.0164 \Delta w \gamma_D$			0.578
D ₇₅	$= - 1.565 + 0.723 \Delta w + 0.0132 \gamma_D + \frac{27.3}{p_c} + 0.857 \Delta w \left(\frac{\gamma_D}{p_c} \right) - 98.4 \frac{\Delta w}{p_c} - 0.00628 \Delta w \gamma_D$			0.449

TABLE 2 (continued)

Compactor Type	Regression Models	R ²
Impact (Lab)		
D ₆₀	$D_{60} = 2.31 - 0.332 \Delta w - 0.0191 \gamma_D + 0.00132 \Delta w \gamma_D + 0.000895 p_c + 10.63 \frac{\Delta w}{p_c}$ $+ 0.0622 \Delta w \left(\frac{p_c}{\gamma_D} \right)$	0.56
D _{pk}	$D_{pk} = 59.04 - 19.43 \Delta w - 0.549 \gamma_D + 0.143 \Delta w \gamma_D + 0.0388 p_c + 194.5 \frac{\Delta w}{p_c}$ $+ 0.655 \Delta w \left(\frac{p_c}{\gamma_D} \right)$	0.76
D ₅₀	$D_{50} = 4.53 - 0.733 \Delta w - 0.0384 \gamma_D + 0.004 \Delta w \gamma_D + 0.00209 p_c + 15.88 \frac{\Delta w}{p_c}$ $+ 0.0846 \Delta w \left(\frac{p_c}{\gamma_D} \right)$	0.685
D ₂₅	$D_{25} = 11.46 - 3.03 \Delta w - 0.083 \gamma_D + 0.0175 \Delta w \gamma_D - 0.000427 p_c + 26.97 \frac{\Delta w}{p_c}$ $+ 0.394 \Delta w \left(\frac{p_c}{\gamma_D} \right)$	0.78
D ₇₅	$D_{75} = 0.595 - 0.083 \Delta w - 0.0046 \gamma_D + 0.000271 \Delta w \gamma_D + 0.000154 p_c + 2.96 \frac{\Delta w}{p_c}$ $+ 0.0194 \Delta w \left(\frac{p_c}{\gamma_D} \right)$	0.61

TABLE 2 (continued)

Compactor Type	Regression Model	R ²
Kneading (Lab)	$D_{60} = 5.85 + 0.0334 \Delta w - 0.0513 \gamma_D - 0.00178 \Delta w \gamma_D + 0.00164 p_c + 0.168 \Delta w \left(\frac{\gamma_D}{p_c}\right)$	0.846
	$D_{pk} = 41.87 - 19.2 \Delta w - 0.381 \gamma_D + 0.147 \Delta w \gamma_D + 0.0149 p_c + 2.473 \Delta w \left(\frac{\gamma_D}{p_c}\right)$	0.615
	$D_{50} = 9.81 + 0.286 \Delta w - 0.0864 \gamma_D - 0.00476 \Delta w \gamma_D + 0.00297 p_c + 0.242 \Delta w \left(\frac{\gamma_D}{p_c}\right)$	0.878
	$D_{25} = 18.37 - 7.77 \Delta w - 0.153 \gamma_D + 0.0579 \Delta w \gamma_D + 0.00438 p_c + 0.951 \Delta w \left(\frac{\gamma_D}{p_c}\right)$	0.91
	$D_{75} = 1.39 + 0.146 \Delta w - 0.0119 \gamma_D - 0.00156 \Delta w \gamma_D + 0.000365 p_c + 0.0293 \Delta w \left(\frac{\gamma_D}{p_c}\right)$	0.736

Technique to Predict Field Equilibrium Water Content

The prediction of field equilibrium water content is usually based on the assumption that the subgrade soil is at a relatively constant above-freezing temperature; in addition, it is assumed that no water gain or loss will occur through the pavement.

The suggested technique first requires the determination of the soil moisture characteristic curve. This curve relates the soil suction to the water content, i.e., for the volume conditions for that soil this is the relation between the water content and its associated capillary pressure (suction) for partly-saturated conditions.

The (capillary) pressure for water is obtained from mercury porosimetry by:

$$p_W = \frac{T_W \cos \theta_W}{T_M \cos \theta_M} p_M$$

where T_W = surface tension of water

T_M = surface tension of mercury

θ_W = contact angle between water and soil

θ_M = contact angle between mercury and soil

p_M = pressure required for mercury

p_M is measured in porosimetry as the pressure required to intrude a given diameter of pore. To obtain the water content which corresponds to the calculated p_W , the volume occupied by the intruding mercury in the porosimetry (a measured quantity) is subtracted from the total volume of pore space of the test specimen.

$$\text{i.e.} \quad w = \frac{(V_{V_T} - V_{V_M}) \gamma_w}{W_s}$$

w = water content

V_{V_T} = total volume of voids

V_{V_M} = volume occupied by mercury

γ_w = density of water

W_s = weight of solids of the specimen.

This procedure will yield the soil moisture characteristic curve from the porosimetry test data by making the calculations at a number of data points, each being the measurement for a specific intrusion pressure. The curve will be valid to values of p_w as large as 25 meters of water.

Now, for the field location the needed quantity is the soil suction. The suction is presumed to be the value of the pore water pressure of an undisturbed sample which has been relieved of the confining pressure on it in-situ.

Thus,

$$S = u - \alpha p$$

where S = soil suction

u = pore water pressure ($\mu = -Z$ = distance above FWL)

α = compressibility factor, 0 to 1

p = in-situ overburden pressure

The magnitude of α is obtained sensibly from:

$$\alpha = 0.027 I_p - 0.12$$

where I_p = soil plasticity index (%)

Thus, knowing the position of the FWL for which the equilibrium water content is being calculated, and I_p for the site soil, the suction is calculated.

The equilibrium water content is then read directly from the soil moisture characteristic curve.

Note The soil moisture characteristic curve can also be defined from pore-size distribution curves, if the raw data for the porosimetry are not available.

$$w = \frac{1}{(1-n)} G_s \left[n - \sum_{i=1}^m f(d_i) \right]$$

where n = porosity of the soil specimen (void volume $\div$ total volume)

G_s = specific gravity of soil solids

$\sum_{i=1}^m f(d_i)$ = sum of the porosity frequencies for pore sizes from the largest measured to the one being considered.

Taking various limiting pore sizes allows the calculation across the water content scale. Knowing the limiting pore diameter, d , for each point, the water pressure associated with that diameter is calculated from:

$$p_w = \frac{4 T_w \cos \theta_w}{d}$$

where the terms are as before.

Summary and Proposed Implementation

This research has clearly shown that pore-size distribution serves as an excellent, sensitive characterization of soil fabric. In addition, it has clearly shown that each behavior property of compacted clays tested has its own unique dependence upon the fabric. Thus, the major conclusion that is reached is that control of the fabric will allow control of the behavior parameters. For the first time a position has been reached where the magnitude of a behavior parameter in-service in the field compacted clay in a direct manner is assured.

This accomplishment can be restated. If the engineer wants a specific magnitude of a parameter in his field compacted clay, he can now determine what characterizations of fabric are associated with that parameter, and, then, using the relationships from this study, prescribe the compaction conditions for the field that will produce that fabric and parameter.

We believe we are on the threshold of being able to directly prescribe compaction specifications to assure given property parameter(s) in-situ, in service. We, however, have assembled the relationships for one (1) clayey soil and for two (2) types of field compaction equipment. A wider coverage of soil types and equipment is needed. Primarily needed are data on the behavior properties of field compacted soils. To make it possible to regulate the field behavior directly, the pore-size distributions of the compacted soils must also be obtained for this is the key that ties together all the data. The technology and equipment for obtaining pore size distributions are not new but some training and encouragement are required to assist the various organizations in its determination.

Characterization of soil fabric and behavior by pore size distribution is matched in promise by its newness. There is an obvious need to educate highway practitioners with respect to the nature and use of the technology, and to challenge them to adapt it to their specific requirements.

The technology needed for the pore size measurements is both relatively simple and inexpensive. It is well within the operational capabilities of all state highway departments and departments of transportation.

As an initial step in implementation of the findings of this research and in developing data on more soil and compaction equipment types the following initial implementation plan is proposed:

- (1) Wide distribution of the research report.
- (2) An information seminar at the IDOH offices in Indianapolis for key personnel from both the IDOH and the FHWA Division.
- (3) Assembly at Purdue University of data collected by Indiana highway engineers on behavior properties of field compacted soils and their pore size distributions.

For the longer term, it is hoped that a more extensive implementation program including many more states would be included with some location designated to receive, assemble, and distribute data collected on many soil and compaction equipment types. Development of an implementation package of training materials might then be very appropriate.

Assembly of a large amount of data in the manner of this report would permit an engineer being able directly to determine which compaction specifications will assure him the presence of the behavior parameters he wishes in the field compacted soil. The days of indirect inference can be ended with some plan for systematic assembly such as the one here proposed.

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